AIRCITY: A VERY HIGH-RESOLUTION
3D ATMOSPHERIC DISPERSION MODELING SYSTEM FOR PARIS.

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Abstract:.
The AIRCITY Project, funded by the EU through the FEDER mechanism, was designed to build an innovative numerical simulation tool to model the dispersion of traffic-induced air pollution at the urban micro-scale. ARIA Technologies is providing the numerical modeling tools with MOKILI and CEA-DAM. AIRPARIF, the Regional Air Quality Management Board of Paris, is building the end user requirements, and LEOSPHERE is providing LIDAR support for field experiments.

Usually, micro-scale simulations of atmospheric dispersion are performed with complete CFD/LES codes, solving complete equations for the flow on very high-resolution meshes. The CPU demand of such calculations is very large, so that only small domains (about 1km) are simulated, in order to keep the execution time reasonable. In AIRCITY, the challenge is to run a high-resolution solver (3m cells) over the whole city of Paris, covering a 12x10km domain.

Key words: Lagrangian particle modelling, urban dispersion modelling, high-resolution wind flow modelling, high resolution dispersion modelling, parallel computing, visualization

INTRODUCTION

To simulate the air flow and end the dispersion of pollutants over a large city with a very high resolution, two main choices were made: (1) the selection of a fast modeling solution (PMSS = Parallel Micro SWIFT SPRAY) with a simplified flow model (Parallel SWIFT a.k.a. PSWIFT) and a lagrangian particle dispersion model (Parallel SPRAY a.k.a. PSPRAY) and (2) the decision to use a massively parallel architecture.

The application of a 3m resolution solver to such a large domain called for a domain separation parallelization of the flow in over about 300 tiles and a particle clouds separation parallelization algorithm for the dispersion calculation. This makes the MPI parallelization more complex than the simpler option to go parallel on particles only, but allows to process arbitrarily large domains, only limited by the memory of the available nodes. Since CEA-DAM operates the largest computing Centre in Europe, with parallel machines ranging from a few hundred to several thousand nodes, it was possible to test the solution on a wide range of parallel computers, from affordable office machines to huge clusters.

The challenge of the AIRCITY project is to provide a solution significantly more precise than the application in urban environments of simpler Gaussian modeling approaches, which are significantly faster. The rationale behind this approach is the following: if a High Performance Computer (HPC) is needed to perform high-resolution simulations for a large city, then the cost of use of a HPC is probably acceptable if it really provides better air quality estimates for a city of over 2 Million inhabitants. In other words, HPC cost nowadays are reasonable enough to justify the challenge.

The focus in the present paper is on the many improvements needed to adapt simulation codes initially designed for emergency response to classical urban applications: management of detailed urban data, coupling with the WRF (or MM5) and the CHIMERE operational photochemical model at AIRPARIF, strategy of parallelization.

Other important physical improvements such as turbulence generated by traffic through coupling with a traffic model, the inclusion of chemical reactions and interaction with background, the parameterization of directional canopy effects, the simulations of trees and river sections, have been made in PMSS. Some of them are described in detail in companion papers in this issue of the 15th Harmonization congress

MANAGEMENT OF URBAN DATA

The AIRCITY simulation tool is designed to run both on : (1) small to average parallel architectures, typically between 5 cores (big laptop) and 50 cores (department cluster), and (2) massively parallel architectures with a few hundred cores up to several thousand cores, usually referred to as High Performance Computers (HPC)

In all cases there is a common target: to process 3D flow calculations and atmospheric dispersion of pollutant substances emitted by traffic at the urban micro-scale with a fast response. Two test domains were designed:

- A limited area of Paris, with a 2.3 x 2.3 km2 surface, and located in the center of the town. In this "Hypercentre" domain we can find a part of the Seine river, alignment of trees, street canyons, large open areas, complex traffic network and several traffic stations operated by AIRPARIF and providing measurements of NO, NO2 and PM10 close to the roads,
- A "Paris" domain covering the whole city of Paris and a buffer zone of 1 km around the city, including a lot of different urban canopy types together with a network of 20 measurement stations operated by AIRPARIF providing background measurements of NO, NO2 and PM10 and levels of concentration close to the roads.

To represent wind field and dispersion with a high resolution in each street of Paris, a 3-meter mesh size is chosen in both domains. It leads respectively to a grid of 758 x 775 nodes in the horizontal plane for the "Hypercentre" domain and of 4675 x 3834 nodes for the "Paris" domain. 35 vertical levels are taken into account with a resolution of 1.5 meter close to the ground and a logarithmic progression up to a height of 800 meters. As a result, simulations are performed on a grid containing an amount of 2.10^7 cells on "Hypercentre" domain and of $6.27.10^8$ cells on "Paris" domain.

In the framework of the AIRCITY project, terrain elevation data at 25-meter resolution and 3D buildings data were provided by the French National Geographic Institute (IGN/IGN-FI). Starting from a file in ESRI shapefile format containing around 5,800 polygons inside the "Hypercentre" domain and 190,000 polygons in the "Paris" domain, the SHAFT pre-processor generates about 77,000 (respectively 2 millions) triangular prisms directly used by Parallel SWIFT (PSWIFT)

Thanks to a joint work with IGN/IGN-FI, the traffic network used by AIRPARIF to define line sources linked to traffic was coupled to the map of 3D buildings. Finally, the number of linear emission sources is close to 38,000 for the "Paris" domain for a total length of 1070 km (respectively 1,300 sources and a total length of 48 km for the 'Hypercentre' domain).

Domains extensions, location of AIRPARIF measurements and traffic networks are displayed on Figure 1:

Figure 1 : "Hypercentre" (left) and "Paris" Domain (right). AIRPARIF measurements stations are represented as green triangles and traffic network by yellow lines

Other urban data like the location of trees were obtained through the ParisData platform and a Python script developed in a commercial GIS has been used to compute average heights and widths of identified street canyons.

METEOROLOGICAL AND CHEMICAL COUPLING

The AIRCITY simulation tool includes meteorological forecasts provided by the WRF meso-scale model. The four WRF grids (see the left picture of Figure 2) are in a scale factor of three with a downscaling process starting from a 45-km resolution domain down to a 1.67 km resolution domain. WRF2ARIA post-processor tool is used to extract in the last WRF nesting level every wind, temperature and humidity vertical profiles that are included into the target PSWIFT domain (see the right picture of Figure 2). These profiles, together with mixing heights values on an extracted 2D grid of WRF, are used by PSWIFT to reconstruct a 3D wind, temperature and turbulence flow at a 3-m resolution.
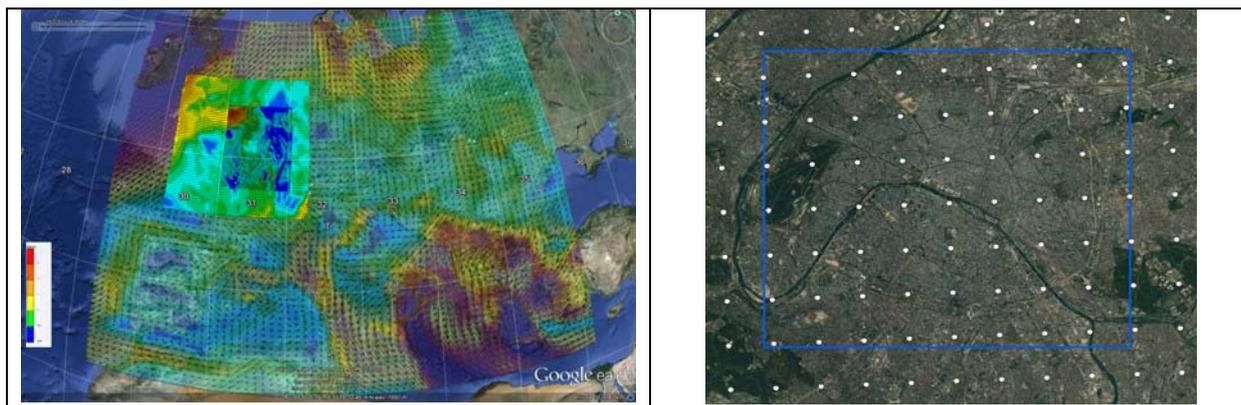
Figure 2: WRF grids (left) and WRF profiles extracted on "Paris" domain (right)

In order to allow the AIRCITY simulation tool to process chemical reactions and to take into account background concentrations due to emissions on the regional scale, PSWIFT is also coupled to the Eulerian multiscale chemical transport model (CTM) CHIMERE (http://www.lmd.polytechnique.fr/chimere/) output of ESMERALDA platform (standing in French for "Multi-regional studies of the atmosphere" – see: http://www.esmeralda-web.fr) provided by AIRPARIF, delivering high resolution forecasts over the Ile-de-France and neighboring regions. WRF2ARIA post-processor was adapted to allow the extraction of CHIMERE vertical concentration profiles over "Paris" domain and its closest neighborhood.
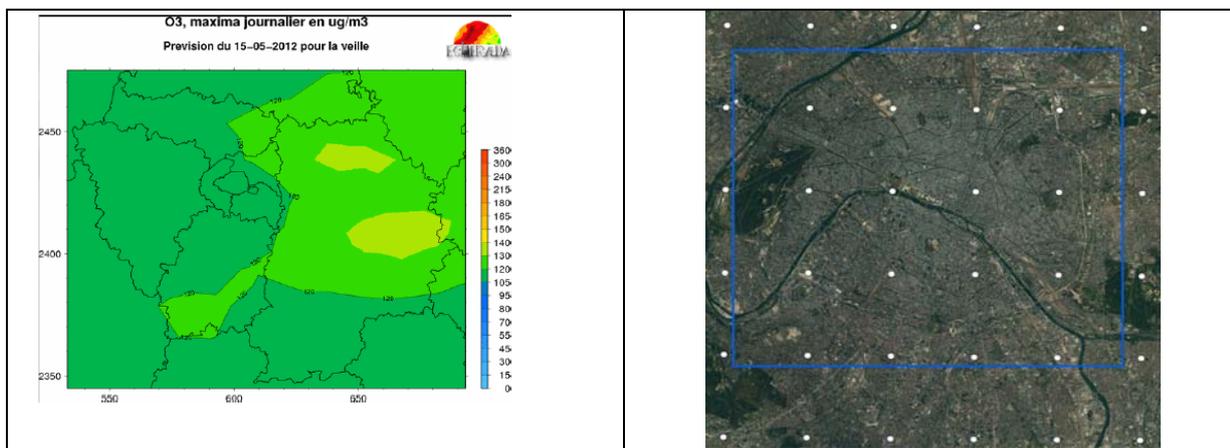

Figure 3: CHIMERE output in ESMERALDA platform (left) and CHIMERE concentration profiles extracted on the "Paris" domain (right)

STRATEGY OF PARALLELIZATION

As both the "Hypercentre" and the "Paris" domains cannot be handled by one single core, they are tiled in sub-domains of 400x400x35 cells. As a result, five cores working in a parallel way allow the computation of the flow and dispersion on the "Hypercentre" domain, and respectively 121 cores for the "Paris" domain.

Finally, on the average parallel architecture of Aria Technologies, flow and dispersion calculation are performed by 9 cores: one master core and two cores working on each sub-domain. On the massively parallel architecture operated by CEA-DAM, tests have been performed between 121 cores and several thousands of cores. Taking into account several cores working on the same sub-domain allows the computation by PSWIFT in a parallel way of meteorological time frames and the distribution of line sources and particles clouds by PSPRAY between available cores, together with the computation of chemical reactions in a parallel way.

On the "Hypercentre" domain, a forecast of 24 hours requires around 10 hours or CPU-time, including the not-parallelized post-treatment performed on WRF, PSWIFT and PSPRAY output in order to publish flow and dispersion results on the web. On "Paris" big domain, CPU time benchmark is still a work in progress in the framework of AIRCITY project but first results are encouraging, as far as a forecast of 24 hours on the $6.27.10^8$ cells grid requires also around 10 hours, with 121 cores when a high minimum resolution of concentration is asked and 481 cores when a low minimum resolution concentration is expected.

VISUALIZATION

Since the "Paris" domain contains a huge number of grid cells, a 24h forecast generates 7 GBytes of WRF output, about 850 GBytes of PSWIFT output and 70 GBytes of PSPRAY output. The smooth visualization of

such large sets of binary and Net-CDF files and the definition of specific ways of visualization adapted to different users, from modelers to citizens of cities are two challenges of AIRCITY project.

As a response to modelers, Paraview 3.14.1 (http://www.paraview.org/) is used on the massively parallel architecture TGCC (http://www-hpc.cea.fr/fr/complexe/tgcc.htm) operated by the CEA. The binary output files of PSWIFT and PSPRAY on the 120 tiles of "Paris" domain are converted in Net-CDF files and visualized in a parallel way using several (up to few hundreds) CPU or GPU cores. Following this methodology, horizontal, vertical slices as well as iso-surfaces can be plotted simultaneously on many tiles. Another target of the AIRCITY project is to publish, in a simple and general way, information about the air quality in a city for all citizens. A natural platform of communication is the web API AirDisplayWidget developed by ARIA Technologies. It allows the visualization of 2D fields and time series of WRF/PSWIFT and PSPRAY variables through a web navigator (see Figure 5).
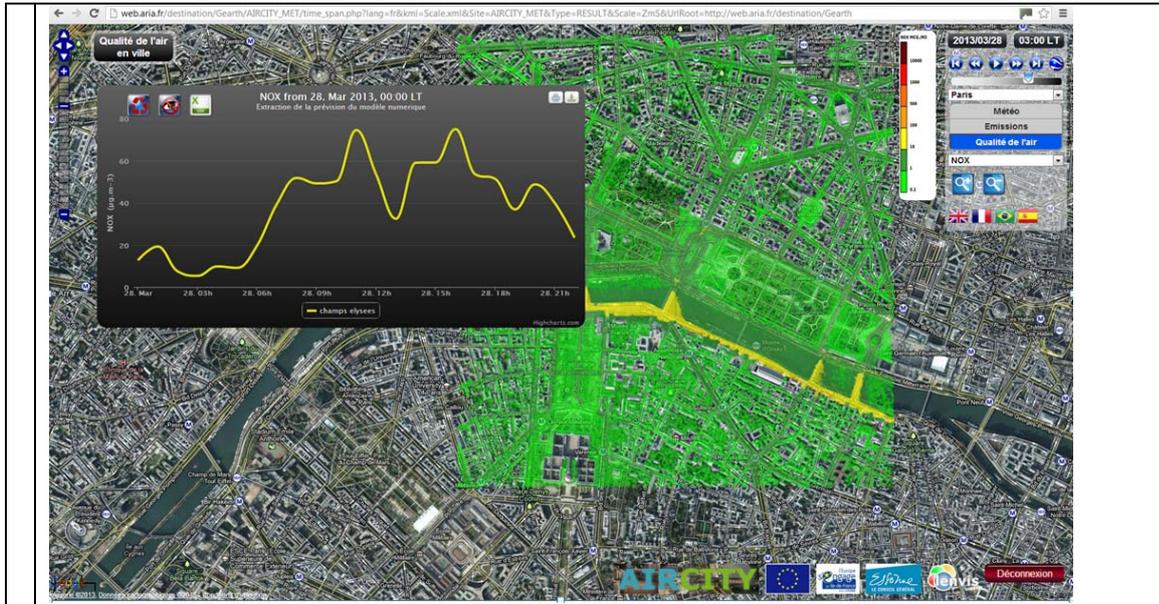

Figure 4: Visualization of a screenshot of AirDisplayWidget on "Hypercentre" domain.

In order to visualize the "Paris" domain output in Google Earth or Google Maps, a set of pyramidal kml files of different resolutions are generated: as a result, as the user zooms on a given area of Paris, pictures of higher resolutions are displayed (Figure 4 and 6). The post-processor used to generate this set of pyramidal kml files includes NCO, Python and Gdal functions.
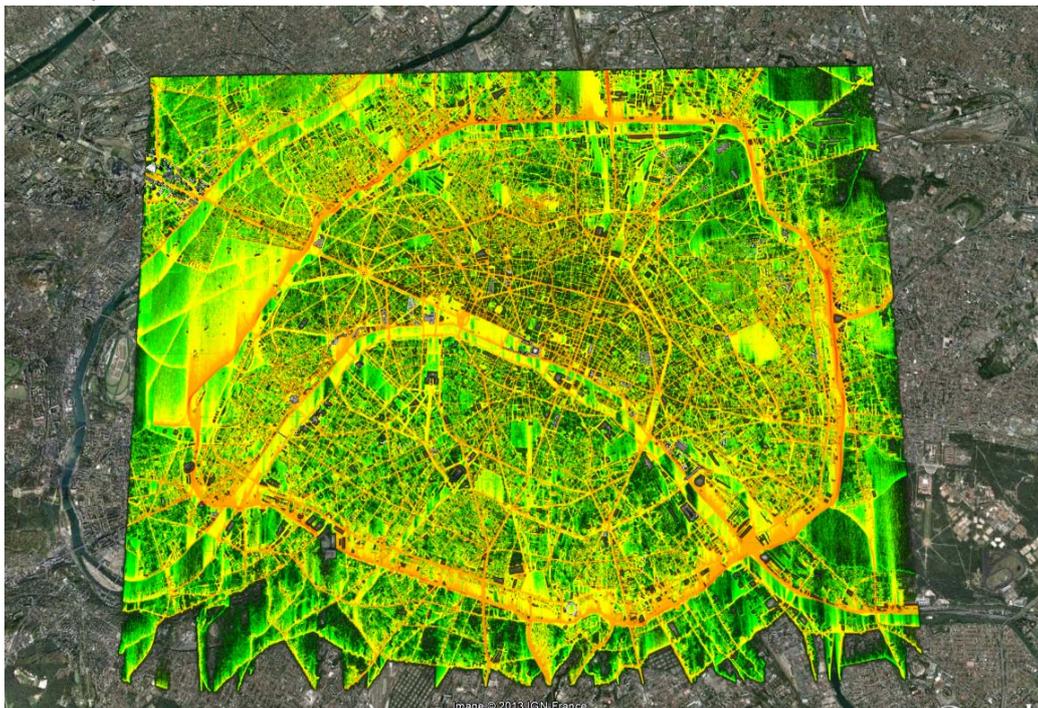

Figure 4: Pyramidal kml in Google Earth: NOx on the whole "Paris" domain.

Figure 6: Pyramidal kml in Google Earth : zoom on the Eiffel Tower area

EXPERIMENTAL VALIDATION

LIDAR measurements of wind and particle concentrations were undertaken in late March 2013 to collect 3D wind data as well as 2D horizontal slices over an area covering about 2 km2 in the South of Paris. The data collected by LEOSPHERE SAS and AIRPARIF will serve as a basis for a detailed validation of the AIRCITY system, comparing both times series at control stations and horizontal patterns of PM concentrations at rooftop level.

CONCLUSIONS

The AIRCITY platform for Paris is now entering its final stages of development, with a release of validation reports scheduled for July 2013. At this stage, we do consider the project as a success since it has already proven the feasibility of very high-resolution 3D simulations at an unprecedented scale for urban simulations. As all operational systems, it is expected that the quality of the output and the simulation skills of the system will continue to slowly increase with time, and with the step by step improvements of all its components. Due to its current architecture, allowing the use of a remote server on the cloud, applying the AIRCITY platform on other cities is an exercise that involves mostly having access to the building, traffic and emissions data, and our team is looking forward to experiment on other sites.

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